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Road Cut Slope Stability Assessment under Region-Specific Rainfall Scenarios in Middle Hills of Nepal

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Abstract

Rainfall-induced landslides, especially in the non-engineered hill roads, have resulted in huge mortality and socio-economic losses in low-income countries like Nepal. In this study, road cut slope stability analysis has been done considering different soil slope scenarios from various road corridors, and incorporating the spatio-temporal distribution of rainfall for site-specific studies in Nepal. The average monsoonal rainfall distribution in the Middle Hills was obtained from satellite GPM IMERG data (2001-2020) to create rainfall regions. We then determined the region-specific rainfall for numerical analysis, and validated them against site slope stability conditions for recent year rainfall from nearby gauged station. Transient seepage analysis was done in Seep/W and Limit Equilibrium Method was employed for slope stability analysis in Slope/W of GeoStudio 2023 using Mohr-Coulomb parameters. Validation for the selected rainfall and soil parameters showed reasonable accuracy to site slope failure conditions and establishes the reliability of the methodology employed for road cut slope stability assessment for regional use. Future scope of this research would be the development of user-friendly versions, with charts and tables for safe cut slope design, and empowerment of field engineers with the knowledge and tools to promote best practices in resilient road construction across vulnerable hilly terrains of Nepal.

Keywords: Cut slope stability; GPM IMERG; Rainfall-induced landslides

1. Introduction

The Nepal Himalayas is highly susceptible to road cut slope failures and landslides due to complex geology, active seismotectonics and intense monsoon (Eslamian et al., 2021). In Nepal, the federal engineers and practitioners generally conduct detailed slope stability analysis in strategic road network and follow the recommendations from Nepal Road Standards 2070 (DOR, 2013), Guide to Road Slope Protection Works, and Roadside Geotechnical Problems: A Practical Guide to Their Solution (DoR-GoN, 2007) for cut slope gradients. However, a majority of the slopes in the Local Road Network are found to be non-engineered and poorly designed with steep cut slopes which have heightened their susceptibility to geohazards.

In low-income countries like Nepal, most of the rural roads are constructed on the basis of “rule-of-thumb” rather than geotechnical investigations due to resource constraints (Robson et al., 2024). This has resulted in haphazard road construction, often without proper drainage, protection, or planning measures in place (Hearn & Shakya, 2017; Paudyal et al., 2023). McAdoo et al. (2018) noted that the non-engineered slopes witness twice as many rainfall-triggered landslides. With the increase in human interventions in the mountainous terrain over the last decade, the incidence of geohazards has increased along road networks (Pradhan, 2021; National Reconstruction Authority and National Disaster Risk Reduction and Management, 2021), claiming numerous lives and disrupting timely emergency access and rescue efforts due to damage in critical infrastructure systems and lifelines.

Around 90% of landslides and debris flow in Nepal occur during the monsoon. In Nepal, the precipitation contribution is approximately 80% of annual precipitation during summer monsoon season (June –September), followed by 12.5% during pre-monsoon (March–May), 4.0% in post-monsoon (October–November), and 3.5% in winter (December–February). Monsoon rains are characterized as high intensity and long-duration rainfall with 2 to 3 day interruptions (Khatun et al., 2023). Studies show that excess precipitation is responsible for triggering floods, avalanches, landslides, and soil erosion in the fragile Himalayan terrain (Aryal et al., 2020; Chalise et al., 2019; Talchabhadel et al., 2019). Dahal & Hasegawa (2008) considered the daily rainfall at failure against cumulative rainfall in the Himalayas and noted that 5 to 90 days of antecedent rainfall lead to landslides triggered by rainfall in general soil slopes.

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The infiltrated rainwater influences slope stability by reducing the shear strength as the wetting front advances (B. Jeyanth, 2019; Jiongxin, 1996; Wen et al., 2023). The increase in the pore-water pressure with the rise of groundwater table results in an increase in seepage force, and a subsequent decrease in matric suction in unsaturated soils (Fredlund, D.G., 1993). This is commonly observed in the failed slopes in extended roadways in hilly terrain when water also infiltrates into slide planes of the undercut slope (McAdoo et al., 2018).

Numerous studies have investigated the influence of rainfall infiltration on the stability of unsaturated slopes, and suggest the selection of appropriate rainfall inputs for unsaturated slope design with due consideration to local soil characteristics and climatic conditions. Lu & Godt (2008) emphasized the need of integrating both the unsaturated soil behavior and rainfall patterns into any model attempting to predict rainfall-induced slope failures. Numerical simulations by Tsaparas et al. (2002) on a typical residual soil slope in Singapore assessed the slope's response to rainfall distribution, saturated soil permeability, initial pore-water pressures, and groundwater table depth. Ng & Shi (1998) used Finite Element Method Seep/W to model pore-water pressures and applied the Limit Equilibrium Method to compute the Factor of Safety of the slopes.

Given the significant human and economic losses due to road cut slope failure, a better understanding of the interactions between Nepal's geological characteristics, topography, and rainfall (Sudmeier-rieux et al., 2019), along with user-friendly guidance (Robson et al., 2025) for roadside excavation is essential for constructing safer roads and mitigating geohazards.

In this study, representative sites along National, Feeder, District and Urban roads have been investigated and analyzed to assess the cut slope scenario incorporating physiographic, meteorological and geological conditions for site-specific adaptation in the Middle Hills. This study assesses cut slope stability under region-specific rainfall scenarios in Middle Hills by integrating satellite-based precipitation, field survey data, and geotechnical modeling and validates them against site failure condition for regional use.

2. Methodology

The region of study is the Middle Hills where the highest number of slope failures are recorded. It extends longitudinally from 80˚ 40´ E to 88˚ 12´ E and witnesses high elevation gradient and climate variability in a short stretch.

2.1 Soil parameters

The soils for the slopes chosen for validation were identified based on simplified field tests. On the basis of the USCS classification, the soil material is categorized into six types: Coarse grained soil (GW, SW, GP and SP); Coarse-grained with non-plastic fines (SC, SM-SC, SM and GM), Coarse-grained with plastic fines (GC and SC), Silt (ML and MH), Low plasticity clay (CL) and High Plasticity Clay (CH).

Mohr-Coulomb shear strength parameters like cohesion (c'), friction angle (φ'), and unit weight (γ), as well as seepage parameters like saturated water content (ϑ_s), permeability (k) and suction were investigated from field data and literature (Bureau of Indian Standards, 1997; Minnesota Department of Transportation, 2007; NAVFAC, 1986). The average values of soil parameters for these soils are shown in Table 1. The hydraulic conductivity function, which shows the effect of increase in soil suction on permeability, was modeled via van Genuchten method in GeoStudio 2023.

Table 1. Soil parameters used for validation

Soil	c' (kPa)	φ' (˚)	γ (kN/m^3)	k (mm/hr)	θ_s	Maximum suction (kPa)
Coarse-grained soil (CG)	1	40	20	50	0.33	5
Coarse-grained soil with non-plastic fines (CGNPF)	5	35	20	11.5	0.41	15
Coarse-grained soil with plastic fines (CGPF)	6	33	20	9	0.40	50
Silt	10	27	18.5	0.97	0.37	100
Low Plasticity Clay (CL)	12.5	18	17.5	0.3	0.40	300
High Plasticity Clay (CH)	20	12	19	0.12	0.47	600

2.2 Meteorological studies

The spatio-temporal distribution of precipitation is influenced by the large scale atmospheric and oceanic circulation patterns, steep elevation gradient, orography, and topography (Hamal et al., 2020). Satellite Rainfall Estimates (SRE) obtained from Gridded Satellite based Precipitation Products (SBPPs) offer high spatial and temporal resolutions. They provide spatially continuous rainfall estimate in the regions where low spatial density of gauged stations (Derin et al., 2019) compromise the accuracy and reliability for necessary interpolations in complex terrains. SREs are especially suitable in countries like Nepal with high climatological variability; challenging terrain for routine maintenance and regular monitoring; and limited resources, where data are often laden with gaps, biases and discrepancies (Barros et al., 2000; Duncan & Biggs, 2012; Kansakar et al., 2004).

GPM IMERG has been known to have superior performance in detecting true precipitation, reduced false alarm, overestimation of the heavy precipitation events and an underestimation of precipitation amount during extreme precipitation events which is crucial in the application of SBPPS in flash flood, and landslide prediction. The seasonal variation of precipitation in Nepal is influenced by the summer monsoon rain convection from South East to North West of the country and by the Westerlies in the West during the winter. GPM IMERG also demonstrates a higher ability to capture the seasonal rainfall variability influenced by the complex topography in the mid and high elevation areas of Nepal over the study region with lower RMSE and higher CC values for all seasonal and spatial contexts compared to other satellite products (Sharma et al., 2020).

Rainfall-induced landslides are the most common during the summer monsoon in Nepal. Therefore, the average monsoonal distribution is considered suitable for regional categorization in this study. The NASA's GPM IMERG V07 Late Run algorithm product from 2001 AD to 2020 AD at spatial resolution of approximately 10 kilometers ($0.1° \times 0.1°$) precipitationCal averaged over the twenty year period has been used to obtain the average monsoonal rainfall raster values (Figure 1).

Further, to incorporate the monsoon rainfall in the numerical analysis, for each region, the daily time series data over the 122 days of monsoonal period from June 1 to September 30 was selected from the Department of Hydrology and Meteorology (DHM) station which recorded the highest recorded monsoon rainfall (2003-2023), and validation was done against recent rainfall records from nearby DHM stations. 42 DHM stations were studied, which were selected based on adequacy for rainfall analysis to determine the representative design rainfall for each regional categories, and their proximity to the investigated field sites chosen for validation.

2.3 Numerical Analysis and Validation

Transient Seepage Analysis using Seep/W was done to model the effect of rainfall time series over monsoonal time period on the groundwater table and pore water pressure conditions for cut slope stability. A hydrostatic initial condition was established at the beginning of the transient seepage analysis with a Piezometric surface. The residual water content was taken as 10%. The finite element results of pore water pressure conditions from parent seepage analysis in Seep/W was integrated into the Slope/W of GeoStudio 2023 for static limit equilibrium analysis for tracking the temporal change in Factor of Safety (FoS) to assess the cut slope stability.

The Morgenstern-Price (M-P) method (Morgenstern & Price, 1965) employs the principles of limit state equilibrium to determine the FoS by analyzing potential failure surfaces and assuming that the slope is in a state of impending failure, ie on the verge of sliding. It considers both force and moment equilibrium, and interslice forces for circular slip surface using half-sine function. The critical FoS obtained over the period of 122 days is analyzed and the minimum value observed over that period is considered for determining the stability of the cut slope under extreme recorded region-specific rainfall scenario.

In this study, a representative site is validated and slope behavior is explained in detail. Results of numerical anlaysis of eight other sites of different soil types selected for validation compared with the slope failure condition at site is also presented to inform further advancement in research.

3. Results and Discussions

3.1 Rainfall regions

High, Medium and Low rainfall intensities were obtained from the average monsoonal distribution and the Middle Hills was categorized as Mid Hill – High (>1,200 mm/year); Mid Hill – Medium (1,000-1,200 mm/year); and Mid Hill – Low (800-1,000 mm/year) as shown in Figure 1.

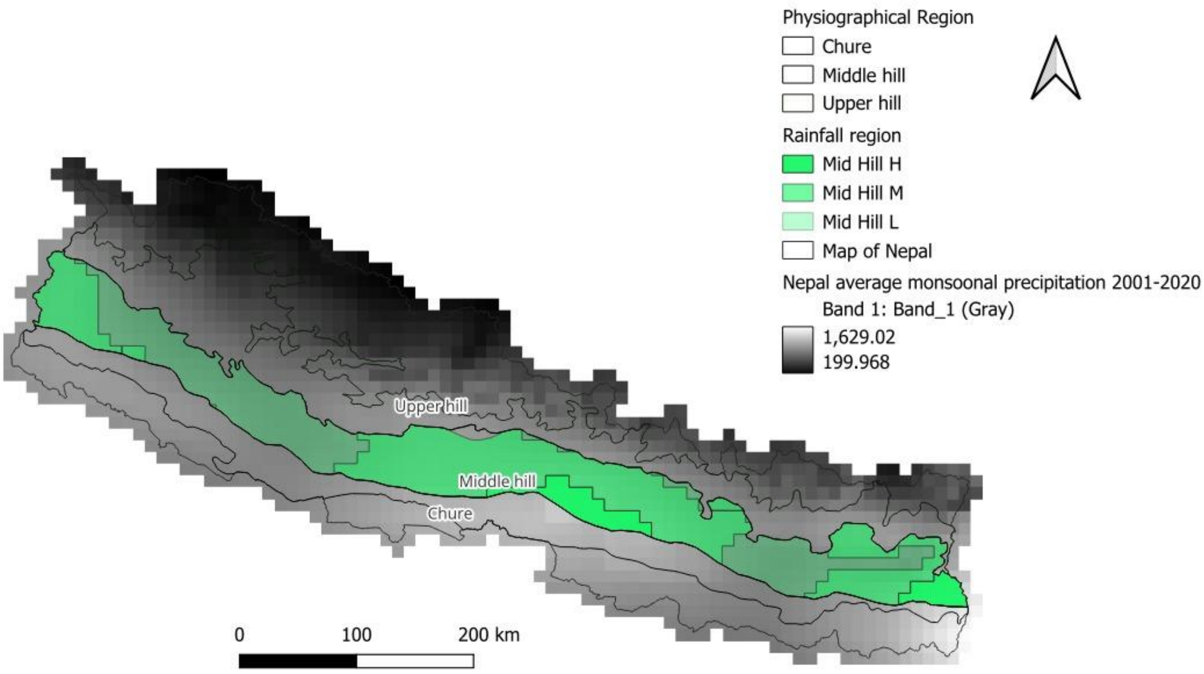


Figure 1. Average monsoonal precipitation (2001-2020) from NASA GPM IMERG is used to obtain regional categories for Middle Hills, namely Mid Hill High (>1,200 mm/year), Mid Hill Medium (1,000-1,200 mm/year) and Mid Hill Low (800-1,000 mm/year). The color band of raster values for average monsoonal precipitation shows that the highest rainfall occurs in the central and eastern region and minimum rainfall in the northern regions.

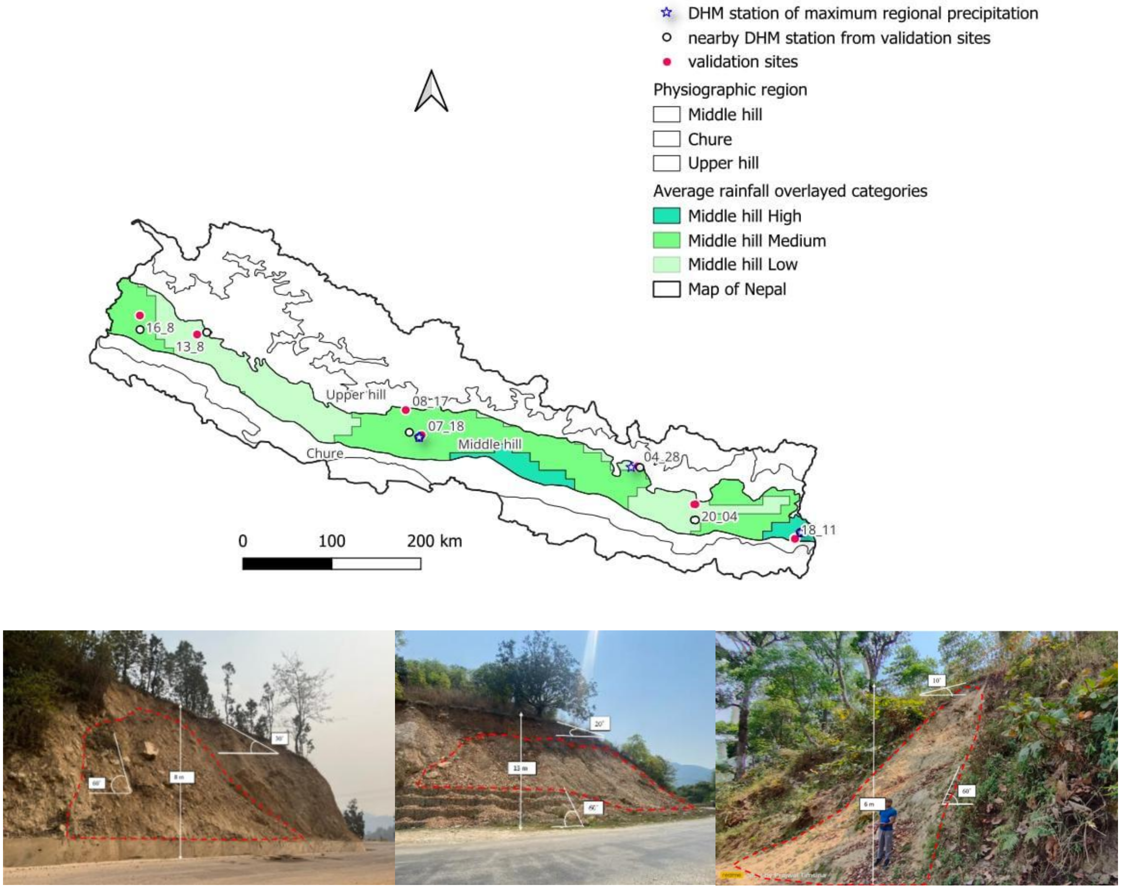
3.2 Representative Rainfall

Firstly, the average monsoonal rainfall rasters from GPM IMERG recorded the highest precipitation as 1629mm and showed a general underestimation in the magnitude of rainfall for use in the numerical analysis. The complex topography (Cattani et al., 2016), and large scale local climatic variation (Gebregiorgis & Hossain, 2013) is attributed to the uncertainties in the performance of SBPPs. SREs adequately captured the spatio-temporal distribution, however, Sharma et al. (2020) showed severe underestimation in mean annual precipitation, chiefly in the well-known high precipitation areas in central Nepal.

Secondly, an uneven daily precipitation is observed during the rainy season with 10% of the total annual precipitation occurring in a single day while 50% is recorded within 10 days of monsoon period (Alford, 1992). Dahal & Hasegawa (2008) suggest that such an uneven rainfall pattern plays an important role in triggering landslides in Nepal. A study by Pink (2024) showed that the daily satellite rainfall estimate are poorly correlated to gauge daily records and implies higher discrepancy compared to the monthly and annual estimates, especially given the insufficient spatial coverage of the gauge network.

In this context, gauged stations capture the recorded precipitation in a daily time series and enable to investigate the behavior of the soil under antecedent rainfall, varying intensities, as well as the short time gap of zero-rainfall between consecutive high magnitude rainfall. Therefore, an analysis period of 122 days of monsoon, corresponding to June 1 to September 30 from the gauged station was considered to capture the absolute minimum Factor of Safety of the cut slope at varying rainfall intensities and saturation states. The long duration allows the assessment of the stability of cut slopes in unsaturated conditions such that the intermediate instability states are not overlooked. This also serves to analyze the site specific variations depending on geographical location and climate for localized conditions.

Therefore, the regional rainfall for numerical analysis was selected as the time series of the Department of Hydrology and Meteorology station that represented the worst case with the highest monsoonal rainfall in any year (2003-2023 AD) among all the stations in that region (Figure 2); 42 stations were considered for Middle Hills.



16_8 CGNPF 07_18 CGPF 18_11 CH

Figure 2. The map shows the Department of Hydrology and Meteorology (DHM) station for Regional Rainfall (station that recorded the maximum rainfall in the regional category) for Middle hill High, Middle hill Medium and Middle hill Low regions. It also shows the nearby DHM stations from the sites used for validation.

3.3 Validation

Validation of sites shown in Figure 2 was done for the regional rainfall and values of soil parameters (Table 1) chosen. The sites for validation are chosen based on material type, status of slope failure and proximity to the available nearby rainfall station for each regional category. Among the nine investigated sites, one is illustrated in detail to assess the road cut slope behavior.

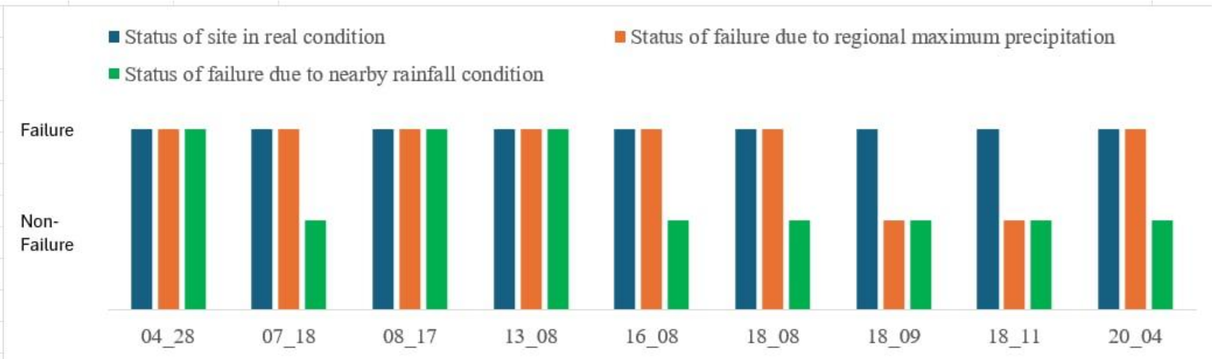


Figure 4 Status of failure from numerical models compared to the real state at site for sites selected for validation in Middle Hills.

Similar analyses for rest of the sites (Gyawali, 2025) showed that 7 out of 9 validated sites analyzed with the regional rainfall failed against 100% of real failure status (Figure 4). It was seen that with 95% confidence in Mc-Nemar's exact test, the true accuracy of the results of slope stability from the validation lies between 93.7% and 45.3% on similar data given the small sample size, which denotes a reasonable accuracy in the selected rainfall and soil parameters for regional generalization, given the high field uncertainties and variability in soil parameter values, as well as contributions from local (de)stabilizing factors. This establishes the reliability of the methodology employed and further informs the soil behavior dynamic under varying rainfall scenarios for accurate slope assessment.

4. Conclusions and Recommendations

Nepal suffers from rainfall-induced road cut slope failures in the fragile mountainous terrain which has resulted in huge socio-economic losses and mortality. The integration of the satellite-based average monsoonal rainfall distribution (GPM IMERG) and the regional maximum monsoonal rainfall event (2003-2023) from the gauged data offers a robust framework for numerical modeling and simulating site-specific scenario to assess cut slope stability across Middle Hills of Nepal. A detailed validation of low plasticity clay road cut slope has been illustrated and the validation results for the rest of the eight cut slopes is presented. The results confirm the reliability of the selected soil parameters and regional maximum rainfall, as well as the use of 122-day monsoon window for dynamic tracking of Factor of Safety to capture critical instability thresholds, offering actionable insights for slope design under varying rainfall intensities.

This study informs further research in the development of Region-Specific Design Charts and Tables with recommendations for safe slope angles for different soil types, cut height and slope geometry that are tailored for quick reference by field engineers and local contractors; extension to the Upper Hills and Chure; and validation through pilot studies in high-risk areas. The sample size of the validation sites could be extended to incorporate the diversity across varied terrain. We also suggest complementing this with training to the local engineers and practitioners on soil identification, choosing the regional zone of the site, and using design charts effectively as a series of diagrams and questions for confidence in local use.

By bridging satellite climatology, geotechnical modeling, and field validation, this approach lays the groundwork for a new generation of resilient road infrastructure in Middle Hills of Nepal, one that is both technically sound and locally grounded.

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